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ENERGY STORAGE CAPACITOR AND DISCHARGE SWITCHING ASSEMBLIES FOR THE PULSED MAGNETIC LENSES AND DEFLECTORS OF AN EXTERNAL PROTON BEAM TRANSPORT SYSTEM

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SUMMARY

A new external proton beam is under construction for new large-scale hydrogen and heavy-liquid bubble chamber experiments. A beam transport system of pulsed magnetic deflectors and quadrupole lenses has been adopted for guiding the proton beam from the ejection window of the Proton Synchrotron (PS) and focusing it onto the external target of the radio-frequency separated secondary bubble chamber beam. The energy storage capacitor and discharge switching equipment of the excitation circuits for the pulsed deflecting and focusing magnets is described, and then performance requirements and essential technical details are specified.

CONTENTS

1. INTRODUCTION

The energy storage capacitor and discharge switching equipment described below is part of a new external proton beam transport system or "beam line". The system guides a beam of high-energy protons from the ejection window of the proton synchrotron and focuses it onto the target of an RF-separated bubble chamber beam in the experimental area. The nature of the particles produced by the impact of the protons on the target as well as their interactions and decay products are identified by a bubble chamber and other suitable detectors.

The most important part of the proton beam transport system is a number of pulsed magnetic quadrupole lenses and deflectors excited by current pulses generated by means of the energy storage capacitor and discharge switching equipment described below.

The focusing and deflection of the beam by the magnetic field of the quadrupole lenses and deflectors must remain reproducibly constant at an accurately pre-determined value during the passage of each proton beam burst from the accelerator. The duration of a beam burst is 5 μsec, and it is repeated at intervals of 500 msec or more as shown in Fig. 1. In principle, continuous d.c. excitation of the magnets could be used, but since the magnetic field is needed for 5 μsec only, the actual useful duty ratio is less than 0.001 per cent and a pulsed type of magnet system has therefore been preferred. This has the advantage of decreasing the electrical duty ratio from 100 per cent down to about 1 per cent, and thus allows a very compact magnet construction with greatly reduced power and cooling installation requirements.

2. BASIC CIRCUIT

The basic circuit for producing the required accurate current pulses is shown in Fig. 2. Essentially it is a high-Q oscillatory circuit which is designed to stop oscillating after the completion of the first period. It works in the following way (Fig. 3): An energy storage capacitor of capacitance C is charged to within $\pm 5 \times 10^{-4}$ of a predetermined voltage U_0 by a thyristor-controlled d.c. power supply during the 500 msec interval between the magnet current pulses. At a given instant, a thyristor switching unit connects the capacitor to the magnet coil via a low-inductance, low-resistance cable. A sinusoidal current pulse is produced through the magnet coil. The thyristor switch is triggered by an external timing programme in such a way that the peak of the current pulse, reached after the first quarter period, coincides with the proton beam burst passing through the magnet. At this instant the capacitor voltage has fallen to zero and starts increasing with reversed polarity, and the diode starts conducting a current which flows through the recuperation coil. Its inductance L_2 is chosen slightly higher than the inductance L_1 of the magnet including the cable in order to ensure extinction of the thyristor switch at the time when the capacitor is still at negative potential and the current tries to reverse. In this way an appreciable fraction of the initial energy is recuperated and transferred back into the storage capacitor with correct polarity. The operation parameters of the various assemblies for all the various magnets of the beam transport system are, in general, not equal, and some parameters must frequently be adjusted as required to match changing beam conditions. A typical set of range values is collected in Table 1.

Table 1

Pulse system parameters, typical range values

1.	Magnetic energy, $\frac{1}{2}$ Li^2	:	0 - 15 kJ
2.	Stored energy in capacitor, $\frac{1}{2}$ CU^2	:	0 - 20 kJ
3.	Magnet current, I_1	:	0 - 3.5 kA
4.	Recuperation current, I_2	:	0 - 3.0 kA
5.	Pulse duration of magnet current, $\pi\sqrt{L_1 C}$	:	0.6 - 6 msec
6.	Pulse duration of recuperation current, $\pi\sqrt{L_2 C}$	:	0.6 - 10 msec
7.	Charging voltage, U_c max	:	5.0 kV
8.	Voltage reversal	:	50%
9.	Voltage recuperation	:	75%
10.	Pulse repetition period	:	1-4 pulses at 500 msec intervals repeated every 8.0 sec
11.	Duty-ratio for discharge circuit	:	1%
12.	r.m.s. current in magnet and recuperation circuit (approx. max)	:	270 A

Precise current measurements are made by means of a low-inductance coaxial shunt and an analogue-to-digital converter that samples the shunt signal at the time of the beam burst. Pick-up coils are included in the circuit for rough current measurements, CRO display of the pulse forms, and for providing the necessary interlock signals.

Constructionally a complete circuit is composed of the following separate parts or assemblies:

i) magnetic lens or deflector;
ii) low-inductance high-voltage pulse cable of 300 m length between magnet and switching unit;
iii) energy storage capacitor and discharge switching assembly;
iv) d.c. power supply for charging the capacitor;
v) control electronics for timing, current adjustment, measurements and protection.

Only items (ii) and (iii) are described more completely below.

3. ENERGY STORAGE CAPACITOR AND DISCHARGE SWITCHING ASSEMBLY

3.1 Cabinet layout and safety switches

The energy storage and discharge switching assemblies are self-contained cabinet-type units located some distance away from the magnetic lenses and deflectors in order to avoid nuclear radiation problems. For safety reasons these units are completely enclosed with sheet metal, and provision is made for appropriate natural air cooling of the circuit components. The interior is subdivided into two regions large enough to house the energy storage capacitor units on one side and the discharge switching assembly including the shielded recuperation coil on the other side. The switching assembly is located in the upper section and is accessible through a front door. A one-pole manual safety switch is provided for short-circuiting and grounding the capacitor terminals. It is operated by a lever outside the cabinet in such a way that the door cannot be opened unless this switch is closed (see Figs. 6a and 6b).

A high-voltage contactor interlocked with the protection circuits discharges the capacitor into a resistor of approximately 1 kΩ and 1 kW average rating with a time constant of about 1 second. It is used when the system is switched off manually or by the interlock circuit in case of certain fault conditions. This switch is closed by gravity forces or spring-load and opened by a 24 V d.c. solenoid. It is fitted with contacts tested to withstand many years of normal operation and at least 10,000 discharges (see Figs. 7 and 14).

The heavy current connections required for the discharge switching circuit inside the cabinet are made from silver-plated copper bars. Provision is made that the thyristor and diode assemblies can be easily exchanged as complete modular units.

Electrical terminals must be suitably located for connection to the cable installation in the double floor (arranged to facilitate modification of experimental installation).

The cabinets must be equipped with eye-bolts for lifting by crane, and have a robust base structure with 120 mm high legs in order to permit easy transport by fork-truck. Front and back panels must be removable.

The equipment must be constructed in such a way that all components can be easily inspected, tested, or exchanged. The execution must conform to up-to-date techniques and standards as required so as to ensure a high degree of reliability under the load condition specified.

The construction must comply with normal safety practice and regulations, and the equipment should be suitably protected so that it can be operated without hazard by experimental personnel possessing no special knowledge of the system.

The energy ratings of the various circuits (Table 2) vary between 2 and 20 kJ, but the circuits may be conveniently divided into two groups according to the energy requirements. This permits standardization of the assembly cabinets into the following two standard sizes:

Type 5-3.5-10: dimensioned for up to 5 kV, 3.5 kA, 10 kJ. This covers the requirements for circuit HD1, HD2, HD3, VD1, VD2 and Q1.

Type 5-3.5-20: dimensioned for up to 5 kV, 3.5 kA, 20 kJ. This covers the requirements for circuit Q2, Q3A, Q3B, Q4A, Q4B, and the spare unit.

The d.c. charging supplies have also been standardized into two types corresponding to 10 kJ and 20 kJ, respectively.

A rating of 20 kJ has been selected for the prototype in order to carry out initial testing at maximum values.

3.2 Energy storage capacitors

The energy storage capacitors required for the various circuits for the initial installation are listed in Table 2, and the capacitor performance requirements are specified together with some technical details in Table 3.

The energy stored in the capacitors, together with their charging voltage, are both dictated by the wave form, duration, and intensity of the currents required to excite the magnetic lenses and deflectors.

It is noted that the capacitors remain under relatively high voltage almost continuously during the operation time, due to the high voltage recuperation which is in the range of 50-75%. But it is also worth mentioning that the capacitors are usually operated at only 80-90% of the nominal 5 kV rating for most of the time. Exceptionally under fault condition the charging voltage may reach 5.5 kV during a short period until the overvoltage protection of the charging supply operates (see also Section 3.4).

An energy of 2.0 kJ per capacitor container has been assumed, since this corresponds roughly to the heaviest weight and largest size that can conveniently be lifted and handled by two persons should replacements be required in the upper part of a cabinet.

For the initial installation each switching assembly contains either 1, 3, 4, 6 or 8 single 2 kJ capacitor units (Table 2) connected in parallel and mounted vertically for best cooling by natural air convection.

The grounding is described in Section 3.6.

Table 2

Nominal circuit parameter for initial installation

(and in brackets, required extension possibilities)

Circuit designation	Proto-type	HD1,2,3 VD1,2 5 equal circuits	Q1	Q2	Q3A Q3B 2 equal circuits	Q4A Q4B 2 equal circuits	Spare circuit	Total for 13 circuits
Peak current, initial (kA) extended (kA)	3.35 (3.35)	2.24 (2.46)	2.88 3.35	1.75 (3.35)	2.65 (3.35)	3.15 (3.35)	3.15 (3.35)	-
Resistance, total (mΩ)	239	176	143	239	239	239	--	-
Resistance, recup.circ. (mΩ)	50	50	20	50	50	50	--	-
Inductance, total (mH)	2.53	2.58	0.30	2.53	2.53	2.53	--	-
Inductance, recup.circ. (mH)	3.40	3.40	0.40	3.40	3.40	3.40	--	-
Stored energy $\frac{1}{2}CU^2$ initially (kJ) extended (kJ)	20.00 (20.00)	7.35 (8.99)	1.45 (1.96)	4.50 (18.40)	10.92 (18.40)	15.88 (18.40)	16.00 (20.00)	70×2 = 140
Charging voltage, initially (kV) extended (kV)	5.00 (5.00)	4.79 (4.74)	4.26 (4.95)	4.33 (4.80)	4.77 (4.80)	4.98 (4.80)	5.00 (5.00)	- -
Capacitance, initially (μF) extended (μF)	10×160 (10×160)	4×160 (5×160)	1×160 (1×160)	3×160 (10×160)	6×160 (10×160)	8×160 (10×160)	8×160 (10×160)	70×160
Pulse duration, initially (msec) extended (msec)	6.32 (6.32)	4.03 (4.51)	0.69 (0.69)	3.46 (6.32)	4.89 (6.32)	5.65 (6.32)	-- --	- -
Energy recuperation, initially (%) extended (%)	36.4 36.4	50.3 (48.7)	52.2 (55.3)	47.8 (36.4)	41.7 (36.4)	38.8 (36.4)	-- --	- -

Note: The above data assume 160 μF, 2.0 kJ at 5.0 kV per container for the energy storage capacitors.

Table 3

Energy storage capacitor data

1. Voltage ratings

1.1	Charging voltage	: 5.0 kV (5.5 kV under fault condition)
1.2	Voltage reversal on discharge	: 50%
1.3	Voltage recuperation	: 75%
1.4	Duration of voltage application between discharge pulses	: 0.5-8.0 sec (see drawing NPA 224-323 (Fig. 4)
1.5	d.c. test voltage applied during 60 seconds	: To be specified
1.6	d.c. test voltage applied during 1.0 hour	: To be specified

2. Discharge current ratings

2.1	Repetition peak current	: 1.0 kA/kJ
2.2	Current pulse duration	: 0.5-10 msec
2.3	Pulse repetition period	: 1-4 pulses at 500 msec intervals, repeated every 8.0 sec (see drawing NPA 224-266) (Fig. 1)
2.4	Cooling	: Natural air at 20 ± 20°C
2.5	Fault current	: Limited only by internal inductance and resistance
2.6	Current test	: 10 discharges with short terminals

3. Life

3.1	Expected life	: To be quoted
3.2	Guaranteed life, allowing 10% failure	: 5 million discharges or 2 years whichever is shorter

4. Execution

4.1	Weight per container	: Max. about 75 kg; exact value to be specified
4.2	Capacitance and energy per container	: Preferably about 160 μF 2.0 kJ

4.3	Capacitance tolerance	: To be specified
4.4	Inductance and self-resonance frequency	: To be specified
4.5	Terminals	: Both poles insulated from casing
4.6	Dimensions and mounting	: Drawing required (dimensions in mm)
4.7	Energy density in joules per litre of volume (terminals, brackets, etc. not included)	: To be specified
4.8	Insulating material	: To be specified
4.9	Impregnation material	: To be specified

3.3 Thyristor assembly

The main switching element of the discharge circuit is formed by a series arrangement of high-power high-voltage thyristors which can hold off at least 5.0 kV under normal operation and are capable of switching currents up to 3.5 kA more than 10 million times. The over-voltage protection circuit of the charging supply operates only at 5.5 kV. Exceptionally under fault condition the thyristors must therefore withstand 5.5 kV (see also Section 3.4). A voltage-sharing and transient suppression network is provided for the thyristors designed according to the manufacturers specifications whilst trying to minimize heat dissipation and charge drain from the storage capacitors. But high reliability components are chosen so that this network is highly unlikely to cause thyristor breakdown.

Specifications of pulsed current ratings of thyristors and diodes as a function of pulse duration, averaging time, and duty-ratio are not commonly indicated in the commercial component data sheets which usually include only normal fault current limits and other data of interest for continuous 50 Hz a.c. duty. Further and satisfactory information on pulse duty ratings are not always readily given by manufacturers. The circuits considered here operate with a duty-ratio well below 1.0%. As a first design criterion for this case, it seems reasonable to assume a permissible pulsed current rating equal to 50-75% of the single cycle (10 msec) fault current rating specified for a.c. applications. Also it is assumed that the initial di/dt value limited by the saturating reactor should not exceed 10% of the limit specified by the manufacturer.

With these assumptions the normal a.c. performance specifications are useful for a first tentative selection of the switching elements for a particular case. The final choice, however, should be made in close consultation with the manufacturer of the solid-state elements and must be based on more exact data or special experimental verification of the performance.

The thyristors, their voltage sharing and transient suppression network, and the isolating transformer of the trigger circuit are combined into a modular unit which can be quickly replaced in case of a failure. All these units have identical physical dimensions. The components are selected to work with natural air cooling.

The firing circuit required for transforming the external timing pulses to more powerful gate pulses suitable for the thyristors used is shown in Fig. 5. The firing circuit assembly is built into a box or drawer located in the discharge switching cabinet. The auxiliary supply voltage (24 V d.c.) and the timing pulse (25 V ± 50%, 1 μsec CERN standard timing pulse) are supplied from an external control box normally located in the cabinet of the d.c. charging supply or from its remote extension unit located in the beam control station, as described in Section 3.

A saturating reactor is connected in series with the thyristors in order to hold off the capacitor voltage for a period of time long enough for all thyristors to turn on smoothly. The reactor also serves to lengthen the useful life by avoiding "hot spots" in the silicon pellet of the thyristor.

The reactor must be dimensioned to match the characteristics of the type of thyristors used. It should hold off the voltage and keep di/dt at an acceptable low value until a sufficient effective area of each thyristor pellet becomes conductive after a time typically larger than 10 μsec, depending on the type of thyristor. Then the core should go into saturation in order to reduce the residual inductance to less than one per cent of the total circuit inductance. The core must have an air-gap since no active resetting circuit is acceptable for reliability reasons.

3.4 Diode assembly

The reverse current through the recuperation circuit which partly recharges the capacitors with the proper polarity flows through a single or series arrangement of high-power high-voltage diodes. They are capable of holding off 5.0 kV (5.5 kV under fault condition) and can carry a current of 3.0 kA for the required pulse duration more than 10 million times. It is clearly preferred that avalanche diodes be used that have a breakdown voltage of 5.00 kV or just slightly higher in order to yield additional protection from overvoltage for both the thyristors and the capacitors. The diodes are protected by a voltage-sharing and transient suppression network similar to that for the thyristors. All these components form a modular unit to meet the same mounting requirements as the thyristor assembly unit.

The components are designed for natural air cooling.

3.5 Recuperation coil

A recuperation coil is connected in series to the diode assembly for storing the energy available when the voltage across the capacitor terminals is zero. This serves to increase the life of the high-precision magnet since it is then not required to carry the reverse current pulses. At the same time the ohmic losses are decreased by using a high-Q coil physically located close to the capacitor and the discharge circuit. The recuperation coil is built into the assembly cabinet, and the magnetic field produced by the coil must be shielded in order to avoid disturbance to the more sensitive parts of the circuit and also to prevent induced currents in cabinet structure. A closed magnetic circuit is not needed but is one possible solution to this problem. For the discharge circuits considered, it has been computed that the inductance of the recuperation coil should be between 1.20 and 1.30 times the inductance of the magnet including the cables. This will give the thyristors the time required for turn-off before the forward voltage is reapplied. A higher inductance value for the recuperation coil would increase the reverse voltage across the capacitor terminals and is,therefore, not desirable for most types of capacitors since it reduces their life or increases their cost.

The coil is dimensioned for natural air cooling, since with a water-cooled construction the reduction in copper does not fully compensate for the additional complications with the cooling circuit. The required characteristics and technical data of the recuperation coils are specified in Table 4.

Table 4

Energy recuperation coil data

1.	Operation voltage	:	5.0 kV
2.	Peak current	:	3.0 kA
3.	Current pulse duration	:	0.7 msec sinusoidal pulse for circuit Q1 7.0 msec sinusoidal pulse for all other circuits
4.	Pulse repetition rate	:	Sequence of 4 pulses at 500 msec intervals repeated every 8.0 sec
5.	Inductance at 1.0 kHz	:	0.40 mH for circuit Q1 3.40 mH for all other circuits
6.	d.c. resistance (tentative data, not critical)	:	20 mΩ for circuit Q1 50 mΩ for all other circuits
7.	Cooling	:	Natural air of 20°C ± 20°C temperature at the entrance to the cabinet
8.	Lifetime	:	10 million pulses
9.	Magnetic shielding	:	See full description
10.	Over-temperature protection	:	To be specified or omitted
11.	Tolerances of inductance and resistance	:	To be specified
12.	Voltage and current tests	:	To be specified

3.6 Measuring devices and ground connection

A high-precision coaxial shunt is provided for accurate measurement of the discharge current. It is designed to be used in the frequency range from 0 to 1000 Hz for currents up to 3500 A and has a resistance of 1.0 mΩ to ensure a high signal-to-noise ratio. Provision is made to dissipate the relatively large amount of Joule's heat created. The resistivity of the material used for manufacturing the shunt has a very low thermal coefficient. A 50 Ω BNC connector is provided as terminal for measuring the shunt signal (see Figs. 8 and 15).

The whole energy storage capacitor and discharge switching circuit is grounded at one end of the shunt, and the cabinet frame is also connected to this point. It is absolutely necessary that there is this one ground connection only in order to avoid ground loops which would disturb the precision current measurement. Obviously the shield of the BNC connector is connected to the ground side of the shunt. The measuring shunts of the various circuits are connected by about 10 m of cable to the central grounding point in the building where the units are located.

Three toroidal pick-up coils or current transformers are incorporated in the appropriate branches of the circuit for relative measurement of the magnet current, the recuperation current, and the capacitor current. Their signals are used to display the current waveforms and also for the protection circuit. These current transformers are built with a secondary winding of a few hundred turns wound on iron cores with air-gaps, large enough not to go into saturation for primary currents up to 3.5 kA. A resistor of 1 Ω terminates the secondary winding which then leads to a BNC connector. The whole arrangement is encapsulated in epoxy (see Fig. 9).

Further data on the shunts and the current transformers are specified in Table 5.

Table 5

Measuring signal requirements

a) Common data

1. Peak current	:	3.5 kA
2. Pulse duration	:	0.5-10 msec
3. Pulse repetition period	:	500 msec
4. Cooling	:	Natural air

b) Shunt

1. Shunt signal	:	1.000 mV/A ± 0.5% over frequency range 0-1 kHz
2. Reproducibility over 1 year and full current range	:	±0.10%
3. Inductance	:	As low as possible (coaxial configuration)

c) Current transformer (tentative data)

1. Transformer signal	:	1.000 A secondary/3000 A primary ±1.0%
2. Approximate core dimension	:	Toroid (or equivalent C-core) of inner diameter 35 mm outer diameter 70 mm width of iron tape 25 mm tape thickness 0.3 mm air-gap 2×0.07 mm

3. Core material	:	Silicon grain-oriented iron
4. No. of turns	:	Primary 1 Secondary 300
5. Winding conductor	:	0.8 mm diameter copper conductor
6. Internal resistance	:	Approx. 1.0 Ω
7. Load resistance	:	1.0 Ω

3.7 Low-inductance high-voltage pulse cables

The cables required for connecting the magnets to their respective switching circuits are all approximately 300 m in length.

The resistive and inductive losses in the pulse cables should preferably be negligibly small compared to the energy transmitted to the magnets. Since no suitable low-inductance coaxial cable is known to exist as a standard commercial product, a symmetrical four-conductor cable is proposed as the best substitute. With diametrically opposite conductors connected in parallel, an inductance of 200-250 nH/m is obtained, or 60-75 μH total for 300 m as compared to the 0.25-2.5 mH inductance of the various magnets. The magnet resistance is in the range 40-140 mΩ, and 300 m of 4×50 mm^2 copper conductor has a loop resistance of 105 mΩ. This is an acceptable value giving a reasonable energy recuperation efficiency.

The cable insulation must withstand the normal operation voltage of 5 kV and preferably at least the same high-voltage test as specified for the magnet coils (12 kV). The cable must also be resistant to nuclear radiation, and polyethylene is therefore preferred as insulating material. An improved execution based on a commercial standard power cable will be satisfactory.

Table 6

Low-inductance HV pulse cable data

1. Inductance	:	200-250 nH/m, max. 75.0 μH for 300 m
2. d.c. resistance	:	350 μΩ/m, max. 105.0 mΩ for 300 m
3. Conductors	:	2×100 mm^2 coaxially arranged, or 4×50 mm^2 symmetrically arranged
4. Insulation test	:	12 kV a.c. peak, 50 Hz applied during 60 seconds first between conductors then repeated between conductors and earth (water electrode).
5. Bending radius	:	To be specified

6.	Peak current pulse	:	3.5 kA
7.	Current pulse duration	:	6.0 msec
8.	Pulse repetition period	:	4 pulses at 500 msec intervals, repeated every 8.0 sec
9.	r.m.s. current	:	270 A r.m.s.
10.	Operation voltage	:	5.0 kV pulses of 6.0 msec duration

3.8 Control electronics

All controls and signal instrumentation for the d.c. charging supply, the energy storage and switching unit, and the magnet are collected together and assembled in a single control box common for each magnet circuit.

This control box and its remote extension units provide the

+25 V, ±50%, 1 μsec timing pulses, the

+24 V d.c. voltage required for the thyristor firing circuit, and the

+24 V d.c. control voltage for the solenoid of the HV contactor.

It also accommodates the voltage and current control and measuring facilities as well as the various protection and interlock circuits and the associated indication.

These control boxes will be located in the cabinets of the d.c. charging supplies, and remote extension units will be located in a central local control station and in a remote beam-control station. All this control equipment will be treated separately, and constructed together with the d.c. charging supplies. Further details are therefore not described in this report.

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APPENDIX I

EXPERIMENTAL MODEL CIRCUIT

An experimental model circuit has been constructed in order to try out principles and components[1] (see Fig. 11). It is assembled in an open frame and has been operated for several million pulses, but so far only at a reduced pulse repetition frequency of only 1 pulse each 2 seconds.

The thyristor firing circuit shown in Fig. 5 works as follows. A positive trigger pulse of 1 μsec duration is applied to the integration network R (56 Ω) C (0.022 μF) via diode 1N914. This network produces an output pulse of sufficient length and amplitude to trigger the thyristor TI 145 A. The capacitor (2.2 μF) is discharged via this thyristor and produces a positive output signal on the primary and, consequently, the secondary windings of the pulse transformer. Diode 10D2 is used to provide a return path for the charge now stored in the capacitor (2.2 μF). The resistor (15 kΩ) limits the charging current for the capacitor (2.2 μF).

Table of Experimental Model Circuit Data

	Item		Type and Supplier
1.	Energy storage capacitor	:	2.0 kJ - 5.0 kV Pyralene impregnated paper insulated. Rectiphase MAE, F74 Pringy par Annecy France.
2.	Thyristors		
	Version A (3 in series)	:	T140N2200 EOG AEG, D 4785 Belecke, Germany.
	Version B (2 in series)	:	TyX390PR32, ASEA, Västerås, Sweden.
	Voltage sharing resistors	:	15 kΩ Rosenthal
	Transient suppression network	:	0.5 μF, 50 Ω
3.	Diodes		
	Version A (2 in series)	:	D400/2800 AEG, D 4785 Belecke, Germany
	Version B (2 in series)		SiD300P30 ASEA, Västerås, Sweden
	Version C (planned)		DSA400-30 BBC, CH5401 Baden, Switzerland.
4.	Recuperation coil	:	Custom made; 3.4 mH air core, unshielded, cooling by natural convection Besson, CH 1260 Nyon, Switzerland (shielded version in preparation by same supplier) (see Fig. 13)

5.	Shunt	:	1 mΩ, air cooled by natural convection, CERN-made, see Fig. 15
6.	Saturating reactor	:	Before saturation 1 mH After saturation 5 μH Iron core cross-section 8.0 cm^2 Silicon grain-oriented iron, C-shape air gap 2 × 0.07 mm number of turns 2 × 9 CERN-made; core supplier Etbls. Martin, F93 Epinay, France (see Fig. 12)
7.	High-tension switch	:	CERN-made, see Figs. 14 and 7
8.	Manual safety switch	:	1 kV - 250 A - 1 pole, type CA 201 A 13/2 short Gardy S.A., 1211 Genève 13, Switzerland
9.	Pick-up coils	:	Air-core coils used with integrator CERN-made
10.	Conductors in discharge switching assembly	:	Copper bars 90 mm^2 cross-section
11.	Pulse transformer	:	See Fig. 10. Besson, CH 1260 Nyon, Switzerland.
12.	Thyristor trigger circuit	:	See Fig. 5 CERN-made
13.	Resistor in series with HT contactor	:	1 kΩ, 1 kW continuous duty woven-band type resistor Schniewindt, D 5982 Neuenrade, Germany.

APPENDIX II

Storage and switching units of existing 2 kV and 3 kV pulse circuits

For the extension of an existing proton beam installation a small series of 2 kV 6 kJ, and 3 kV 12 kJ energy storage and switching assemblies have recently been constructed and brought into operation for a bubble chamber experiment. The 2 kV version has storage capacitors only for 6 kJ, and sufficient space is also available for the charging supply unit and the control box which are incorporated in the top left quarter of the assembly cabinet. Both the 2 kV and the 3 kV circuits are a simplified recuperation circuit provided by the magnet of the main discharge circuit and a diode connected in antiparallel across the main thyristor switch. Otherwise these circuits are basically similar to the 5 kV circuits described in this report. Some photographs of the existing assemblies are therefore shown in Figs. 16 and 17 in order to give an approximate idea of the appearance and constructional aspects of the new equipment.

REFERENCE

1) R. Grüb, H. Pflumm, F. Völker: Solid-state switches for capacitor discharge circuits for pulsed beam transport application. A description of the design, construction and performance of the solid-state switches for the 3 kV and 5 kV experimental model circuits. Written report not yet available.

Figure captions

Fig. 1 : Operation cycle of external proton beam transport system (Drawing NPA 224-266).

Fig. 2 : Capacitor discharge circuit diagram (Drawing NPA 224-262).

Fig. 3 : Current and voltage wave forms of capacitor discharge (Drawing NPA 224-265).

Fig. 4 : Capacitor voltage as function of time (Drawing NPA 224-323).

Fig. 5 : Thyristor trigger circuit diagram (Drawing NPA 224-322).

Fig. 6a : Tentative layout of 10 kJ assembly (Drawing NPA 224-332).

Fig. 6b : Tentative layout of 20 kJ assembly (Drawing NPA 224-333).

Fig. 6c : Detailed drawing NPA 224-293 of 3 kV, 12 kJ assembly cabinet (available on request).

Fig. 7 : High voltage contactor (CERN-made version) (Drawing NPA 224-325).

Fig. 8 : Coaxial measuring shunt (CERN-made version) (Drawing NPA 224-324).

Fig. 9 : Current transformer, preliminary design (Drawing NPA 224-326).

Fig. 10 : Trigger pulse transformer (Drawing NPA 224-336) (available on request).

Fig. 11 : Experimental model circuit 5 kV, 20 kJ (photo CERN 31.11.68 and 33.11.68).

Fig. 12 : Saturating reactor (photo CERN 23.11.68).

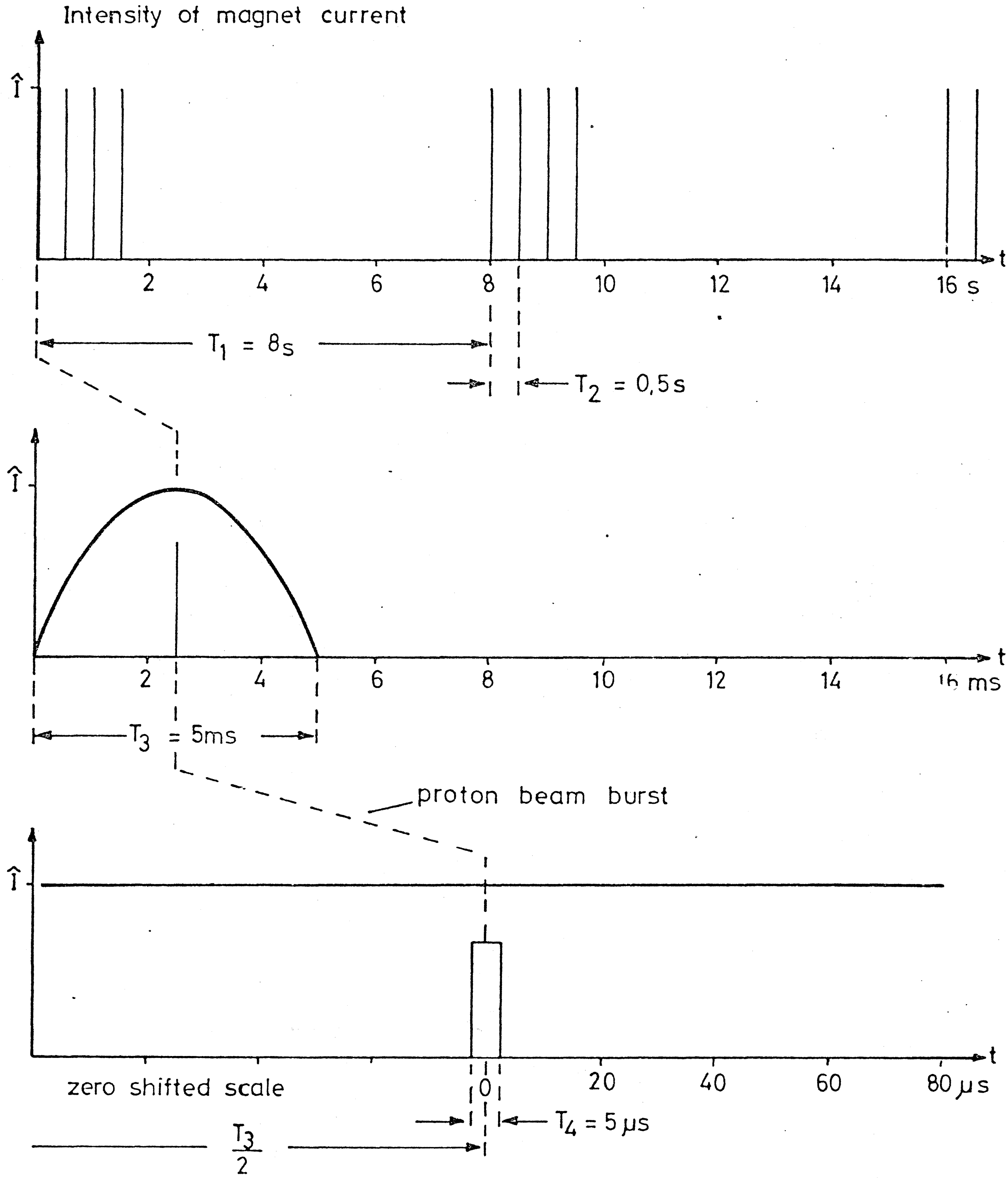
Fig. 13 : Recuperation coil, unshielded version, 600 mm outer diameter (photo CERN 25.11.68).

Fig. 14 : High-voltage switch (photo CERN 26.11.68).

Fig. 15 : Coaxial measuring shunt (photo CERN 24.11.68).

Fig. 16 : Capacitor discharge assembly 2 kV, 6 kJ incorporating switching assembly, storage capacitors and d.c. charging supply in a single assembly cabinet (photo CERN 41.11.68).

Fig. 17 : Energy storage and discharge switching assembly 3 kV, 12 kJ. Shielded recuperation coil not yet mounted (photo CERN 40.11.68, 38.11.68 and 43.11.68).



useful duty ratio : $\frac{T_4}{T_2} = 10^{-3}$ %

electrical duty ratio : $\frac{T_3}{T_2} = 1$ %

FIG. 1

OPERATION CYCLE OF EXTERNAL PROTON BEAM TRANSPORT SYSTEM

224 – 266 – 4
ER 26.9.68.

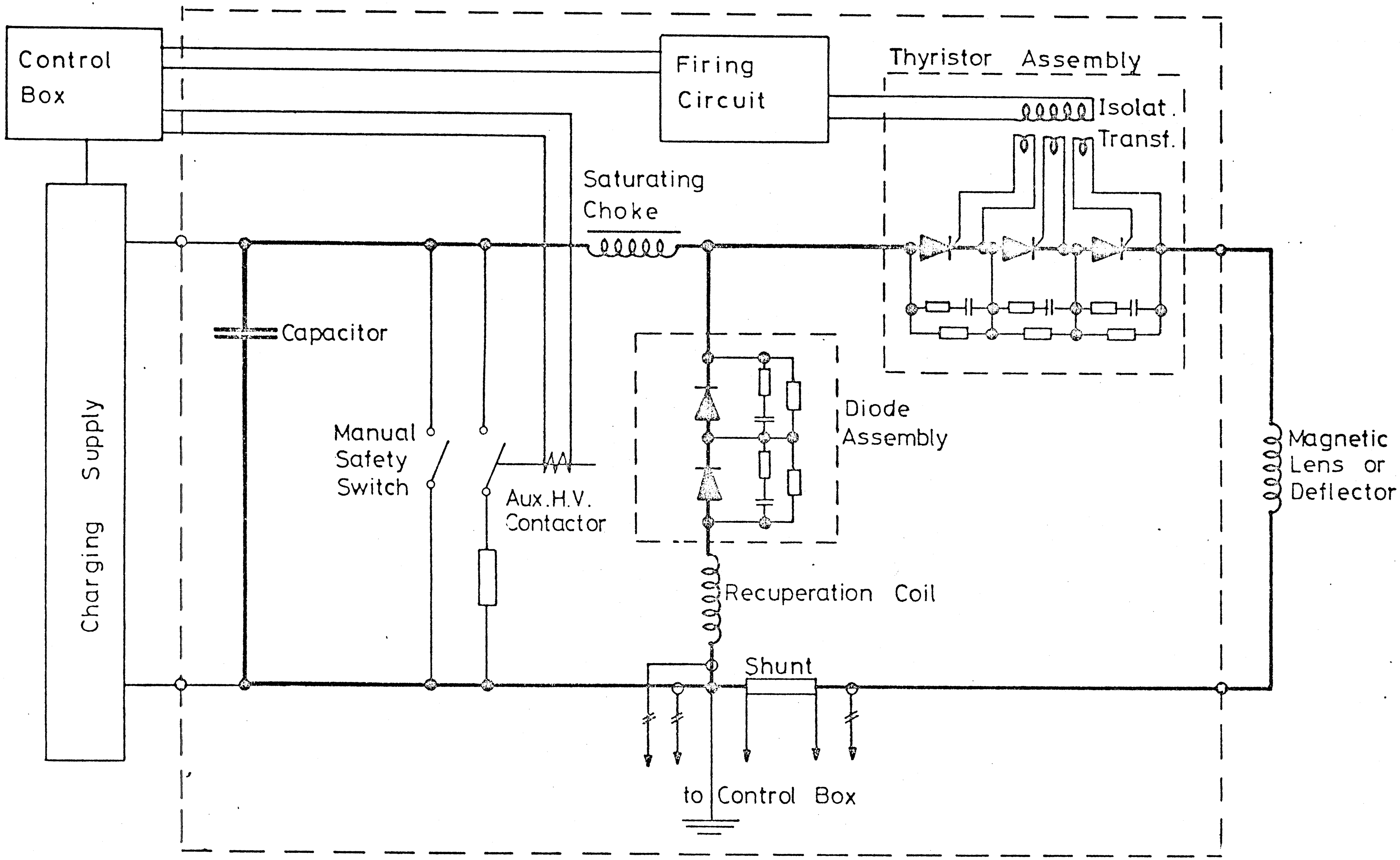


FIG. 2 CIRCUIT DIAGRAM OF ENERGY STORAGE CAPACITOR AND DISCHARGE SWITCHING ASSEMBLY.

224_262_4 A

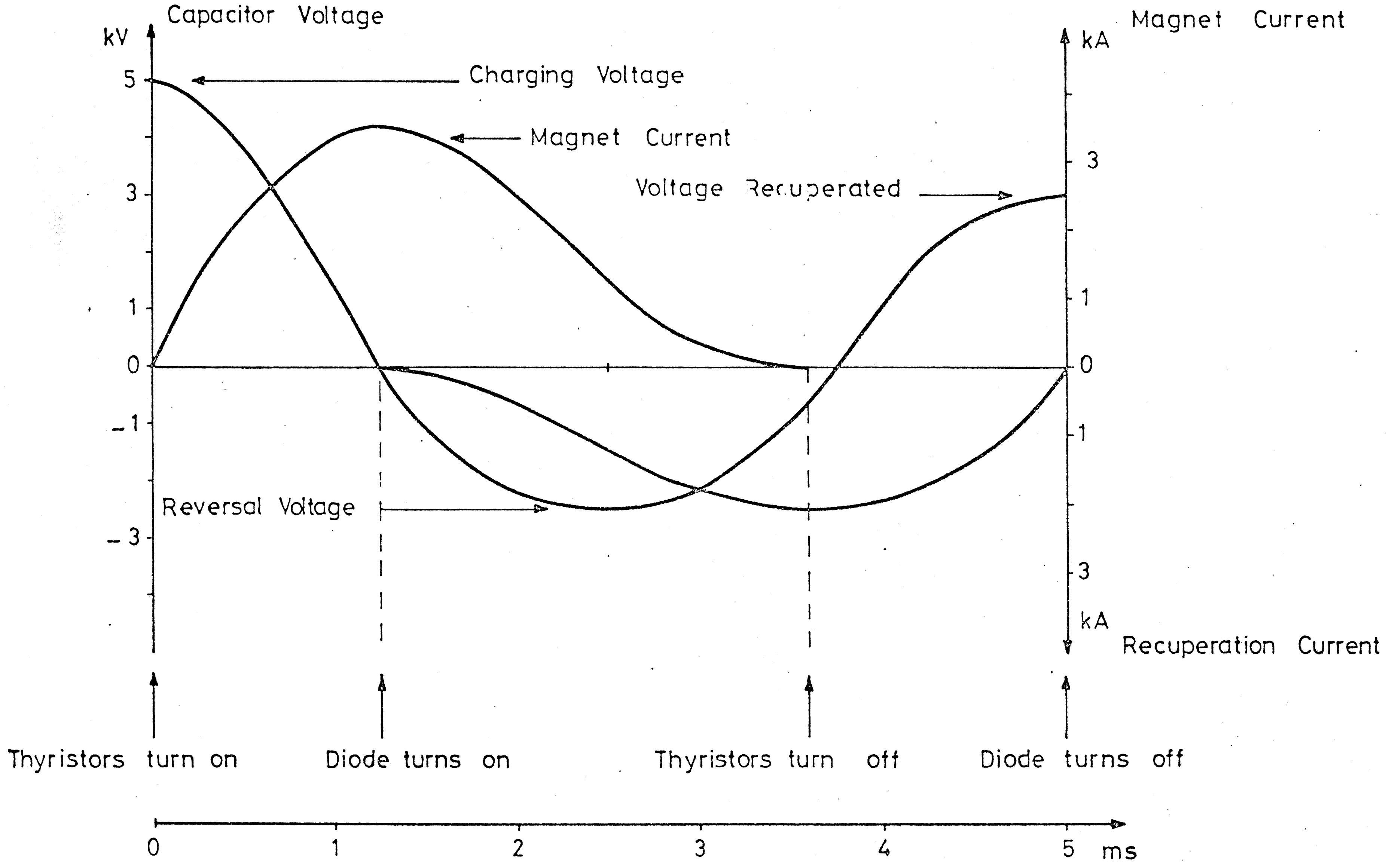


FIG. 3 CURRENT AND VOLTAGE WAVE FORMS OF CAPACITOR DISCHARGE

224-265-4

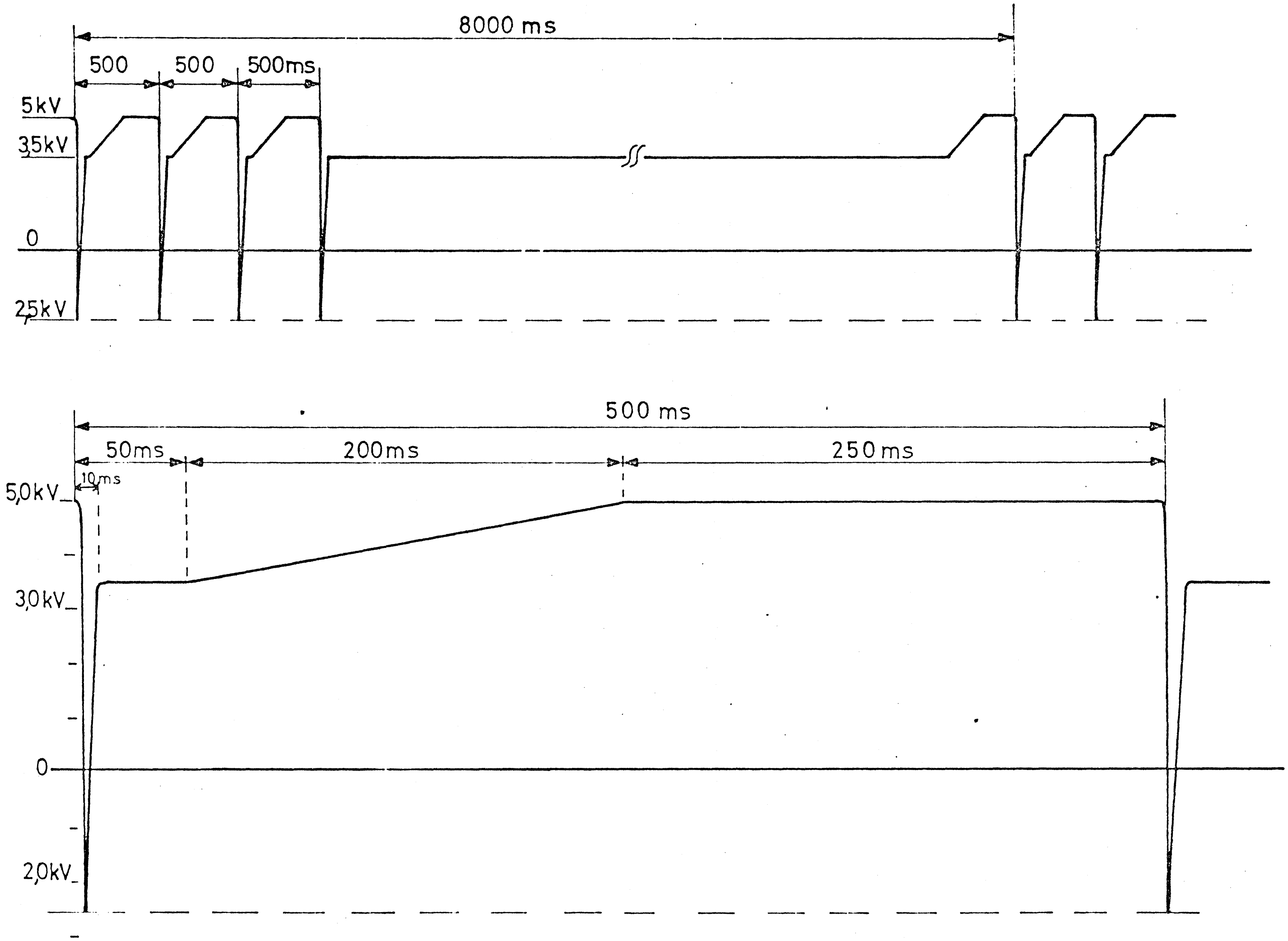


FIG. 4 CAPACITOR VOLTAGE AS FUNCTION OF TIME.

224-323-4 A
FR 5.11.68

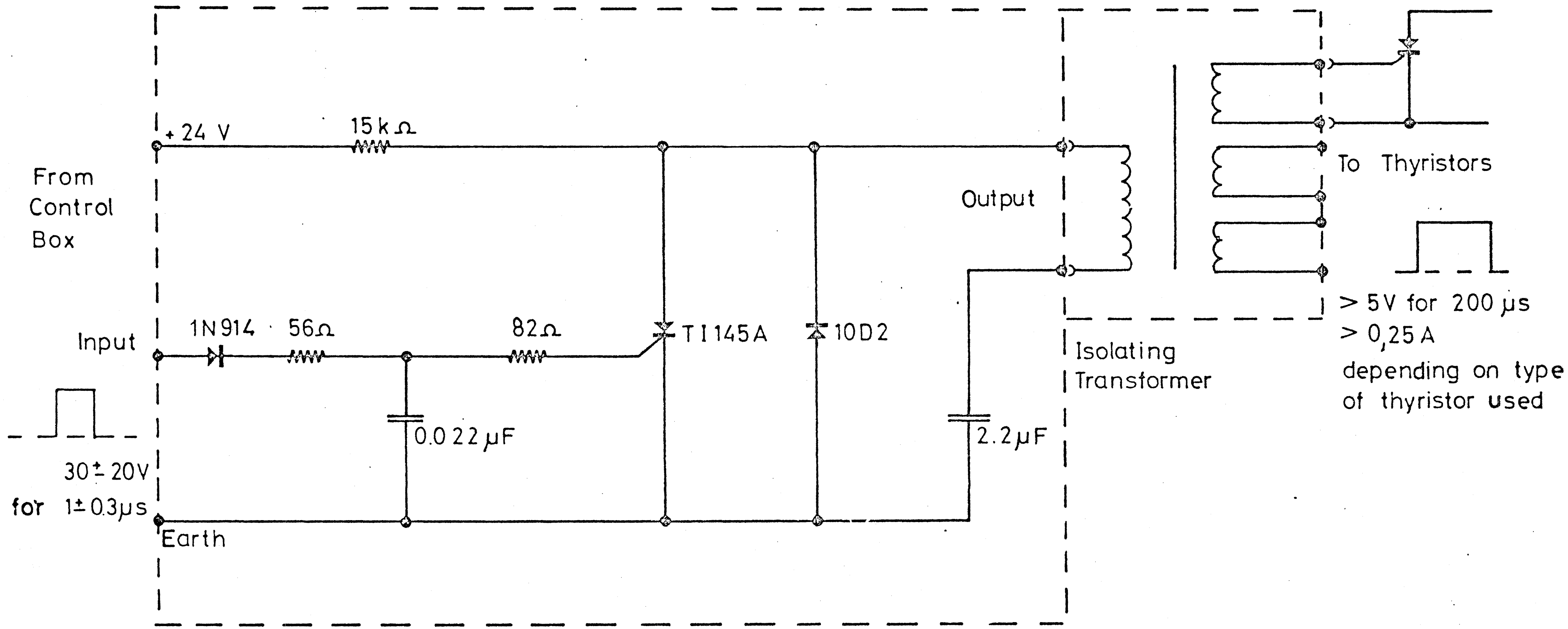
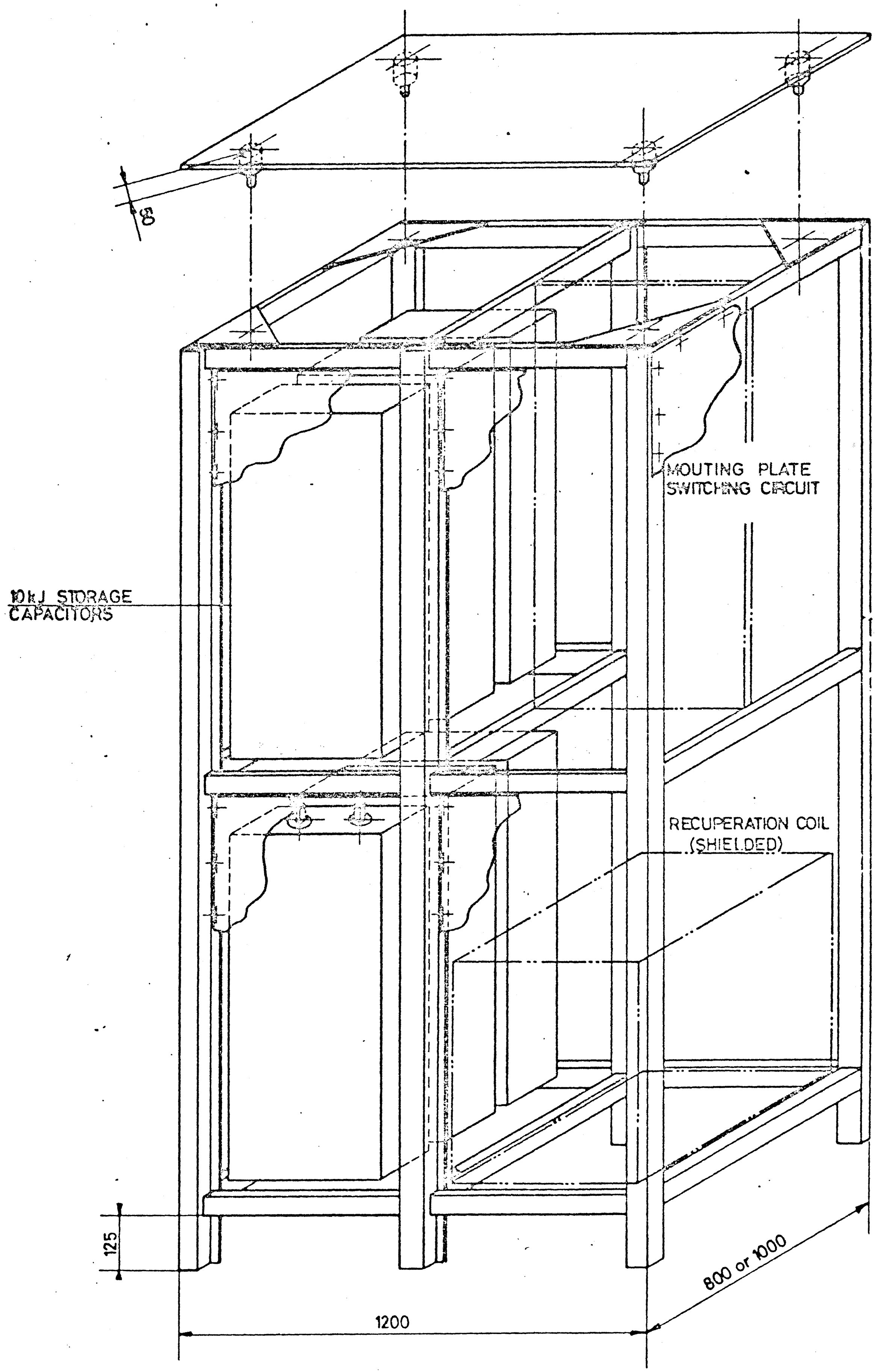


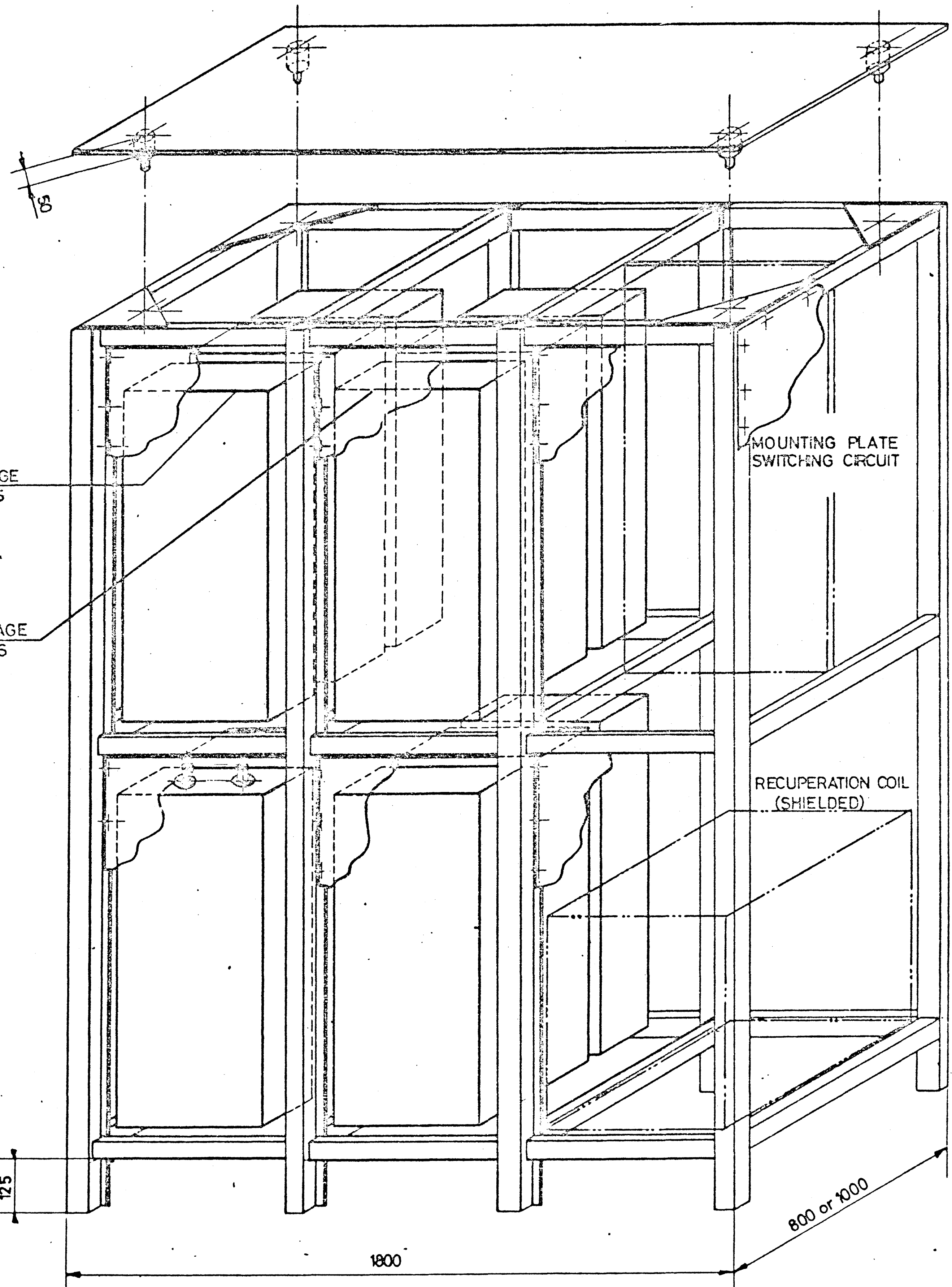
FIG. 5 THYRISTOR TRIGGER CIRCUIT

224-322-4
ER. 5.11.68.



TENTATIVE CABINET LAYOUT FOR 10kJ ENERGY STORAGE CAPACITOR AND DISCHARGE SWITCHING ASSEMBLY

NPA 224_332_4
E.M 14.11.68



TENTATIVE CABINET LAYOUT FOR 20kJ ENERGY STORAGE CAPACITOR AN
DISCHARGE SWITCHING ASSEMBLY

NPA 224_333_4
E.M 14.11.68

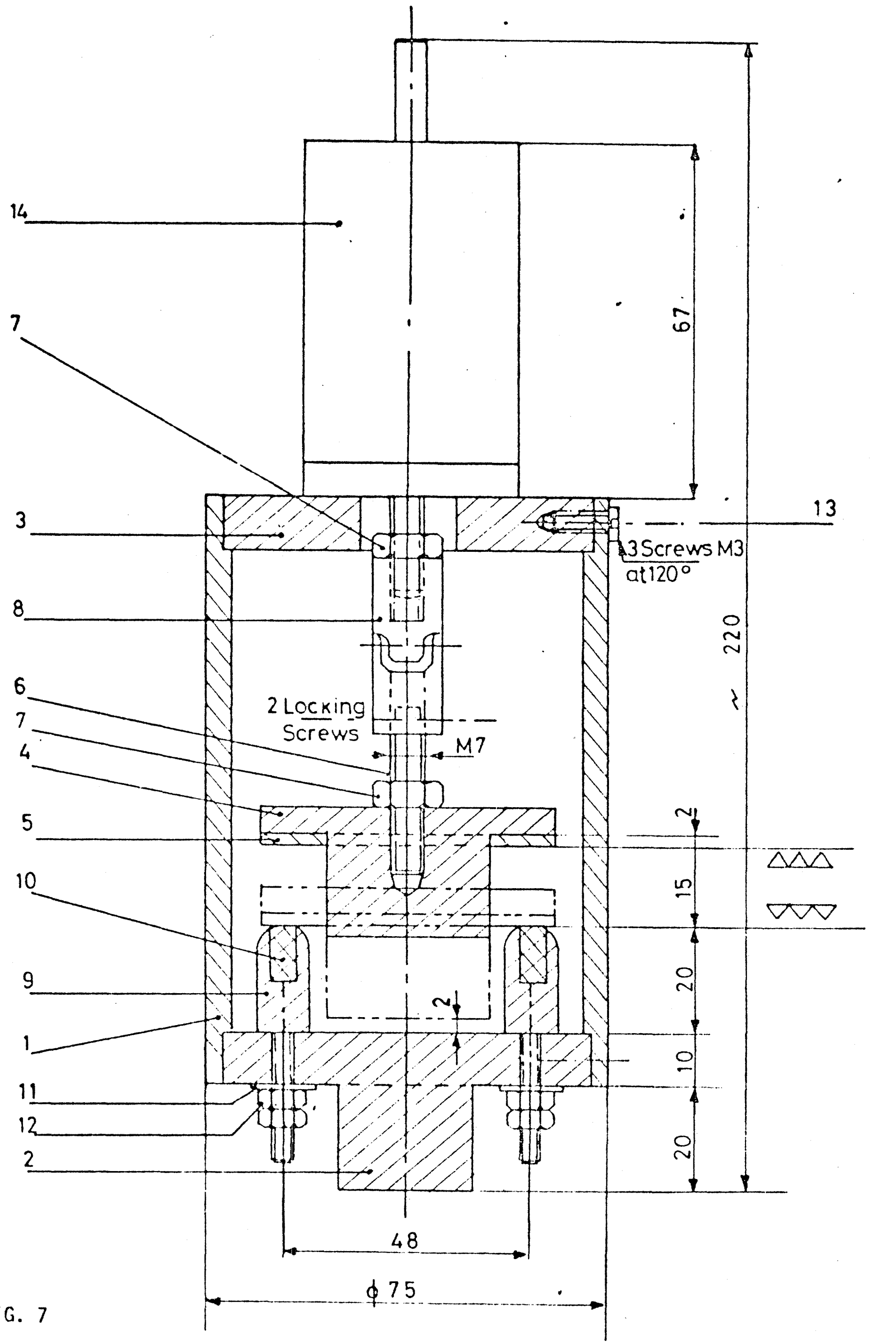
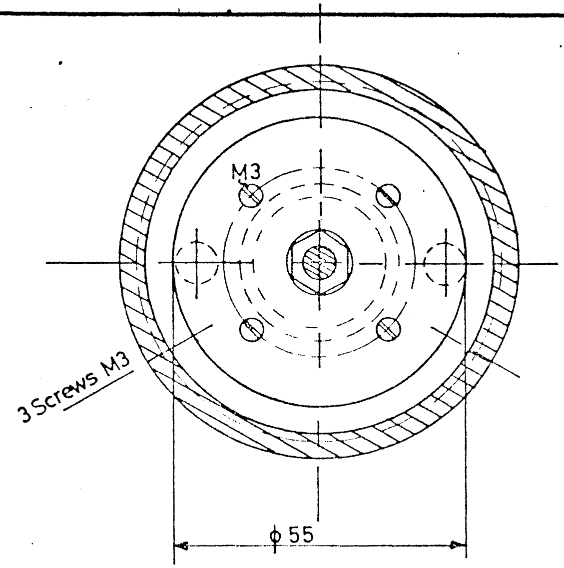


FIG. 7



III	II	I	Désignation	Pos.	Matière	Observations
		1	Solenoid	14		Harting Typ HM 41, 100%ED 24 V=
		6	Screws M3 L = 10	13	Nylon	
		4	Nuts M5	12	Brass	
		2	Washers 5.3 x 12	11	Brass	
		2	Rods Ø 5L = 10	10	Tungsten	Press fit into. item 9
		2	Rods Ø 10 L = 45	9	Brass	
		1	Joint	8	Steel	
		2	Nuts M 7	7	Steel	
		1	Threaded rod M 7 L = 30	6	Steel	
		1	Ring 55 x 32 th. 2	5	Tungsten	Epoxy resin on item 4
		1	Upper contact support	4	Perspex	
		1	Lid Ø 70 thickness 10	3	Perspex	
		1	Base Ø 70 thickness 30	2	Perspex	
		1	Tube Ø 75 x 65 L = 110	1	Perspex	
Nombre de pièces			Désignation	Pos.	Matière	Observations

Mod.	Date	Nom	Tolérances générales		
A			de	à	±
B			de	à	±
C			de	à	±

Ensemble — S. Ensemble

Dessiné —
Contrôlé —
Vu —
Remplace —
Remplacé par —

Echelle

PULSED BEAM TRANSPORT

HIGH VOLTAGE SWITCH

Dossier N° — Dossier N° — Dossier N°

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224 – 325 – 3 A

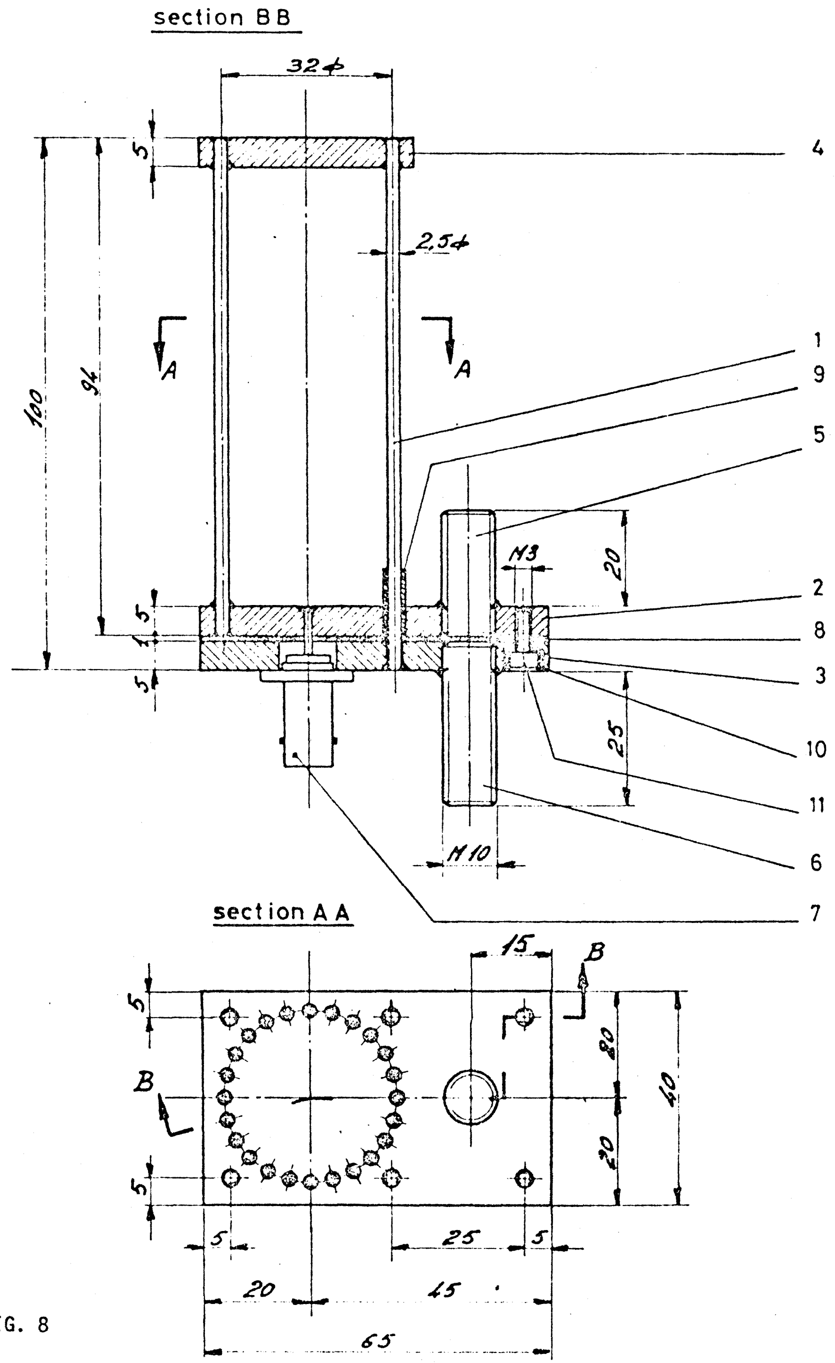

FIG. 8

III	II	I	Désignation	Pos.	Matière	Observations
		6	srews M3 x 2	11	Brass	
		6	insulating bushing	10	Nylon	
		12	insulating sleeves, L = 12	9	Nylon	
		1	insulating foil 40 x 65 x 1	8	Nylon	
		1	BNC connector 50 Ω	7		srewed on item 3
		1	current connector M10 x 30	6	Brass	silver soldered
		1	current connector M10 x 25	5	Brass	silver soldered
		1	end plate	4	Copper	
		1	outer connector plate	3	Copper	
		1	inner connector plate	2	Copper	
		24	rods 2,5 ⌀ x 94	1	Manganin	silver soldered

Nombre de pièces

Mod.	Date	Nom	Tolérances générales		
A			de	à	±
B			de	à	±
C			de	à	±

Ensemble — S. Ensemble

Dessiné	5.11.68	[illegible]
Contrôlé		
Vu		

Remplace

Remplacé par

Echelle 1:1

Pulsed beam transport

Coaxial shunt

Dossier No — Dossier No — Dossier No

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DIVISION NPA

224-324-3

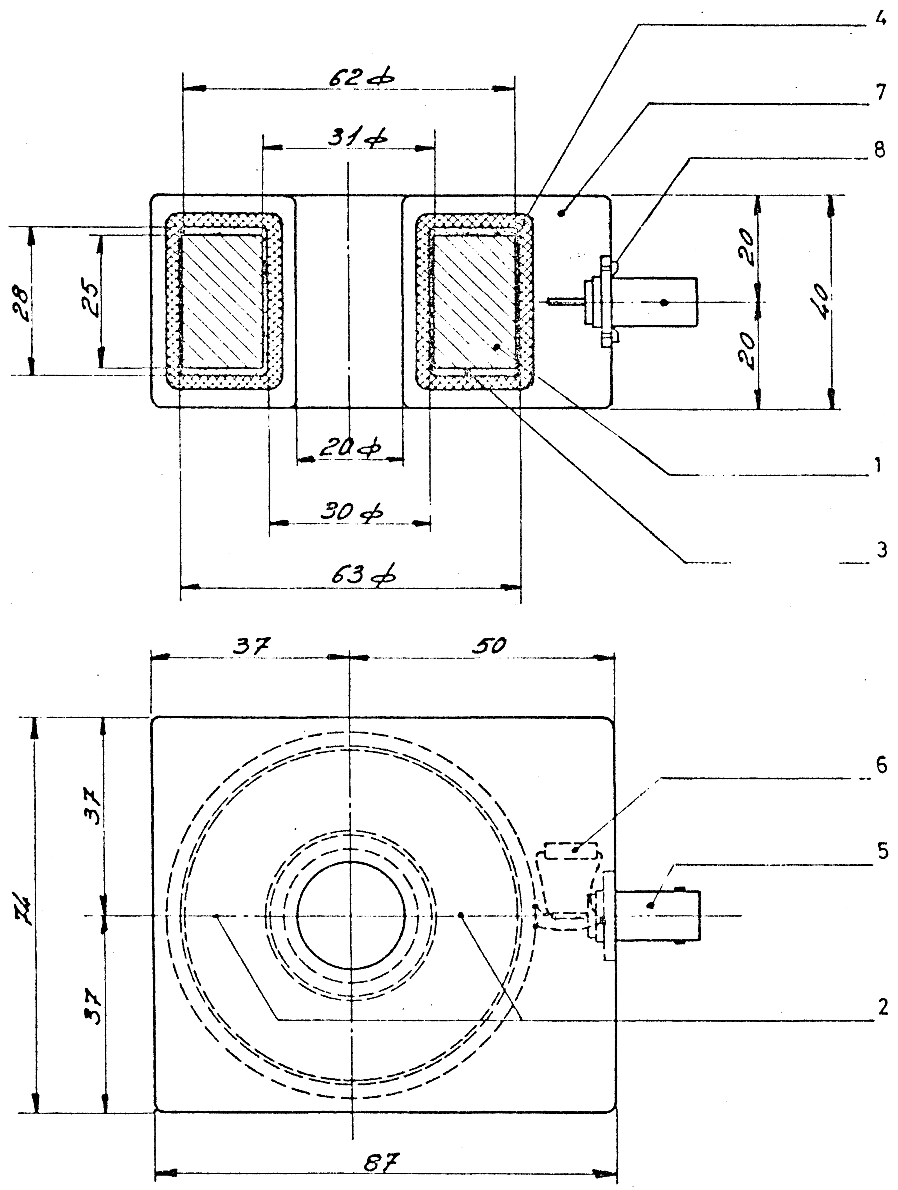

FIG. 9

III	II	I	Désignation	Pos.	Matière	Observations
		4	screw M3 x 6	8	Steel	
		1	encapsulation	7	Epoxy resin	
		1	resistor	6		1Ω - 1W, Low inductance
		1	BNC - connector	5		
		1	secondary winding ⌀ 0,8	4	enameled copper wire	300 turns in 3 thightly wound layers
		1	insulation	3	insulating material	
		2	gap thick 0,07	2	Mylar	
		1	core	1	Iron	grain oriented silicon iron

Nombre de pièces

Mod.	Date	Nom	Tolérances générales		
A			de	à	±
B			de	à	±
C			de	à	±

Ensemble | S. Ensemble

Dessiné 5.11.68 [signature]
Contrôlé
Vu
Remplace
Remplacé par

Echelle 1:1

Pulsed beam transport

Current transformer

Dossier No. | Dossier No. | Dossier No.

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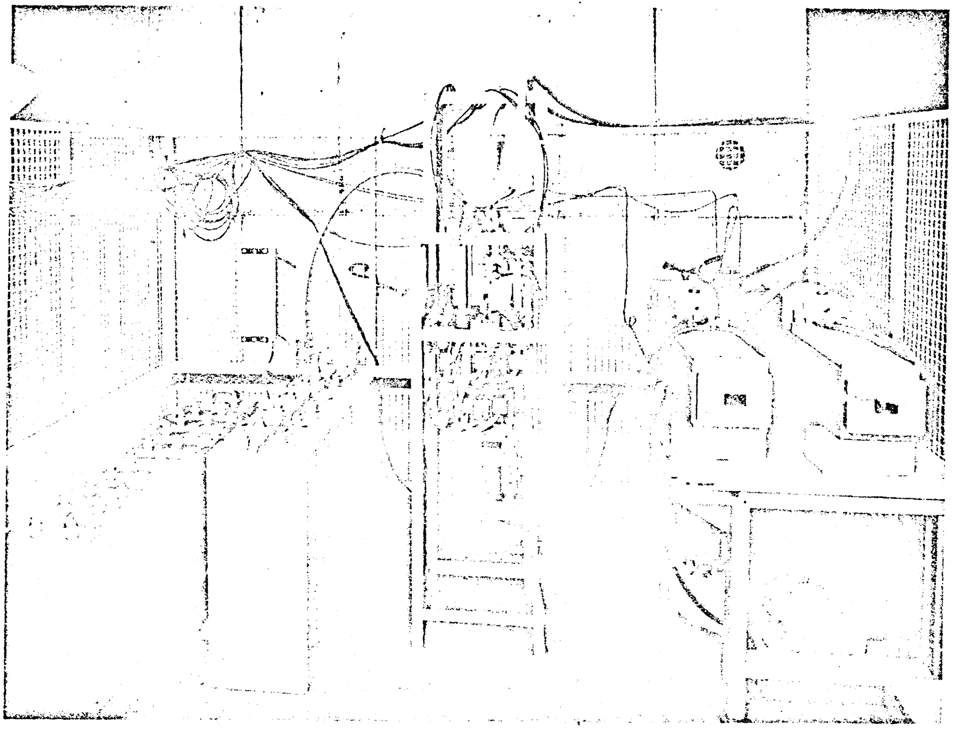
224-326-3



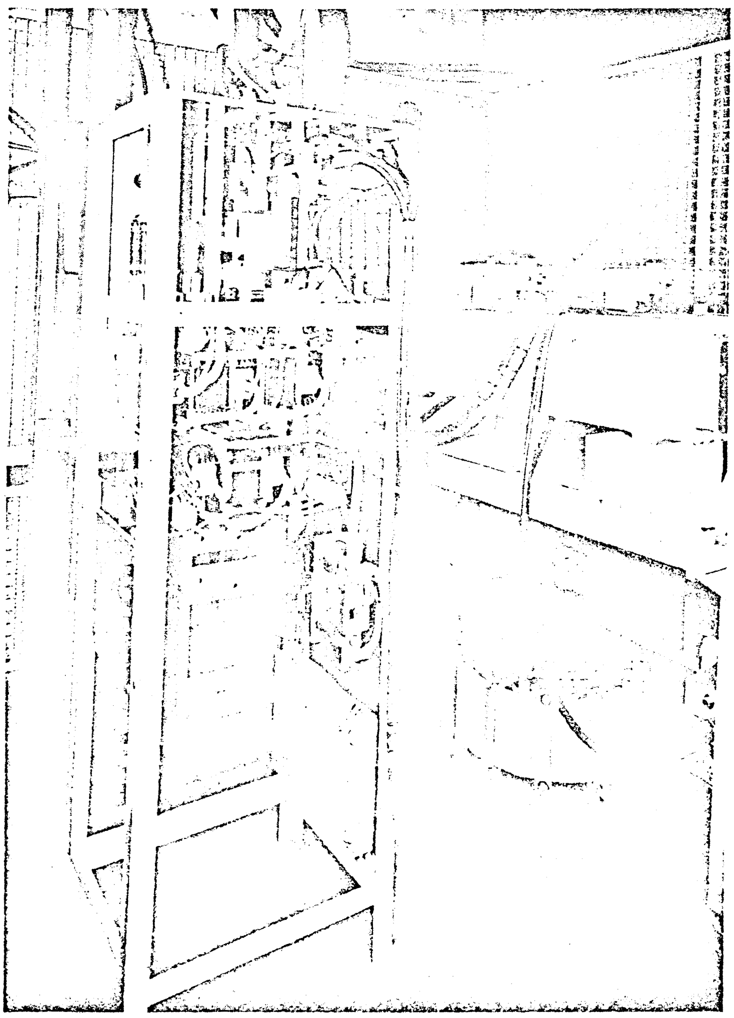


Fig. 11 Experimental model circuit 5 kV, 20 kJ, version A

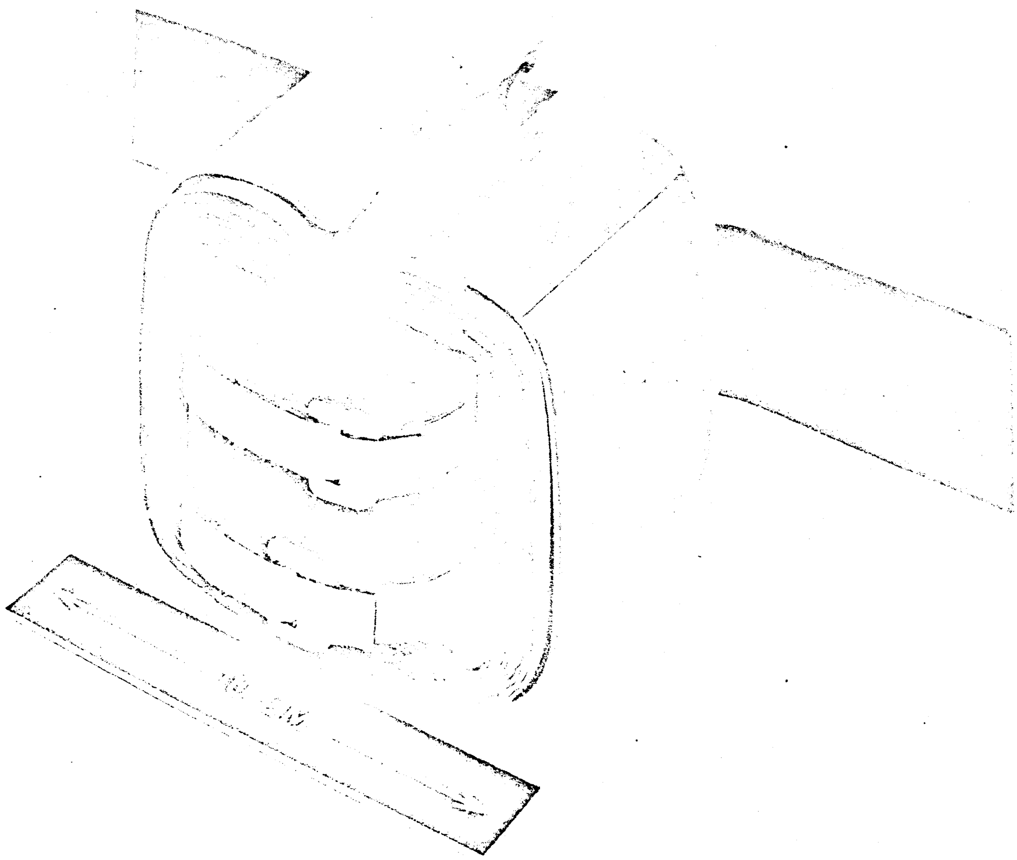


Fig. 12 Saturating reactor

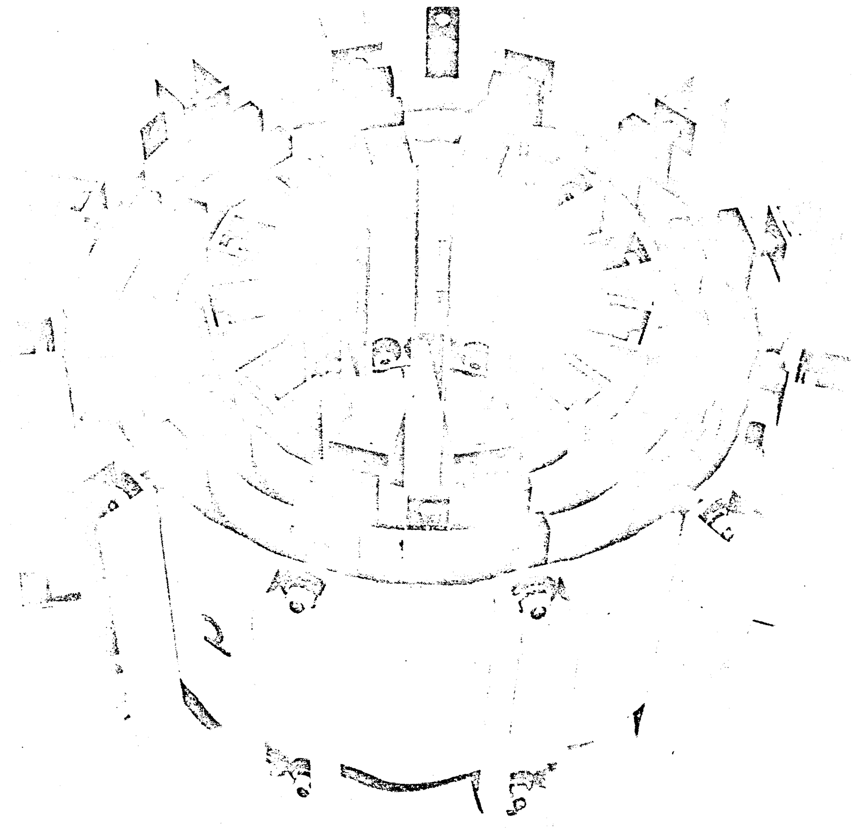


Fig. 13 Recuperation coil, unshielded version
600 mm outer diameter

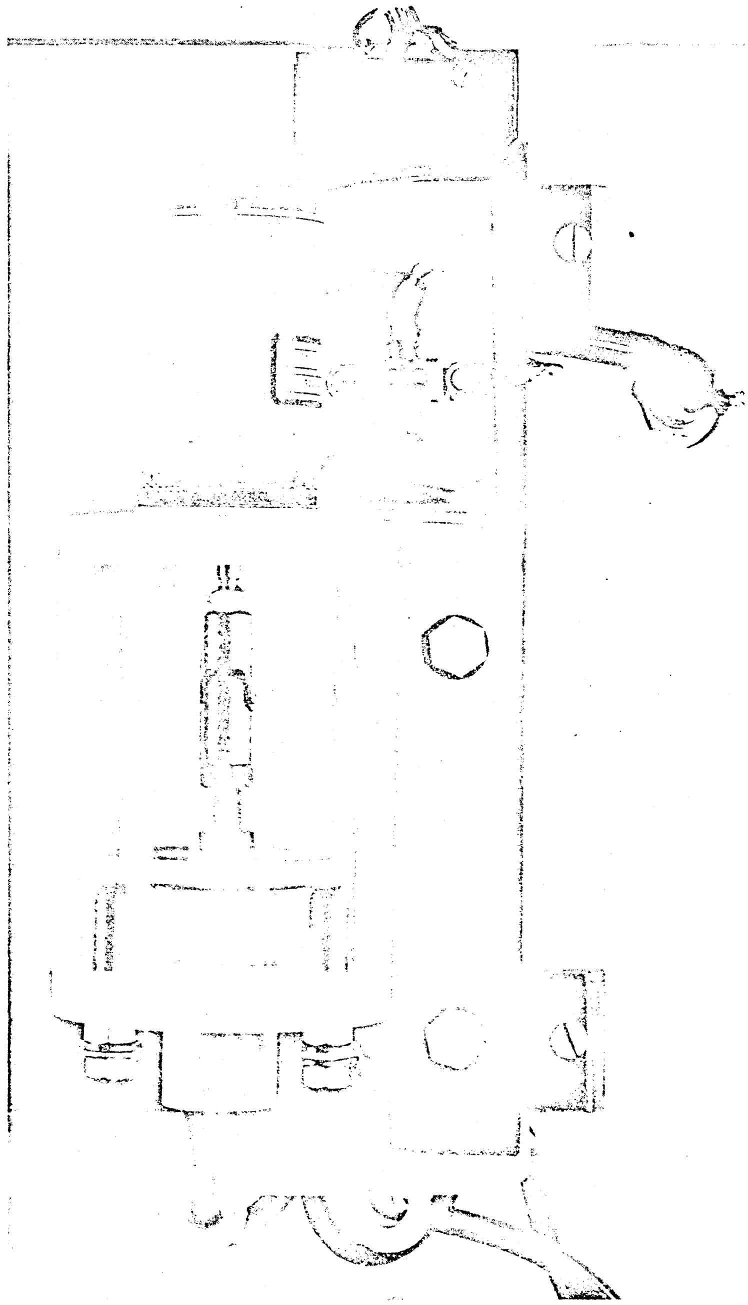


Fig. 14 High-voltage switch

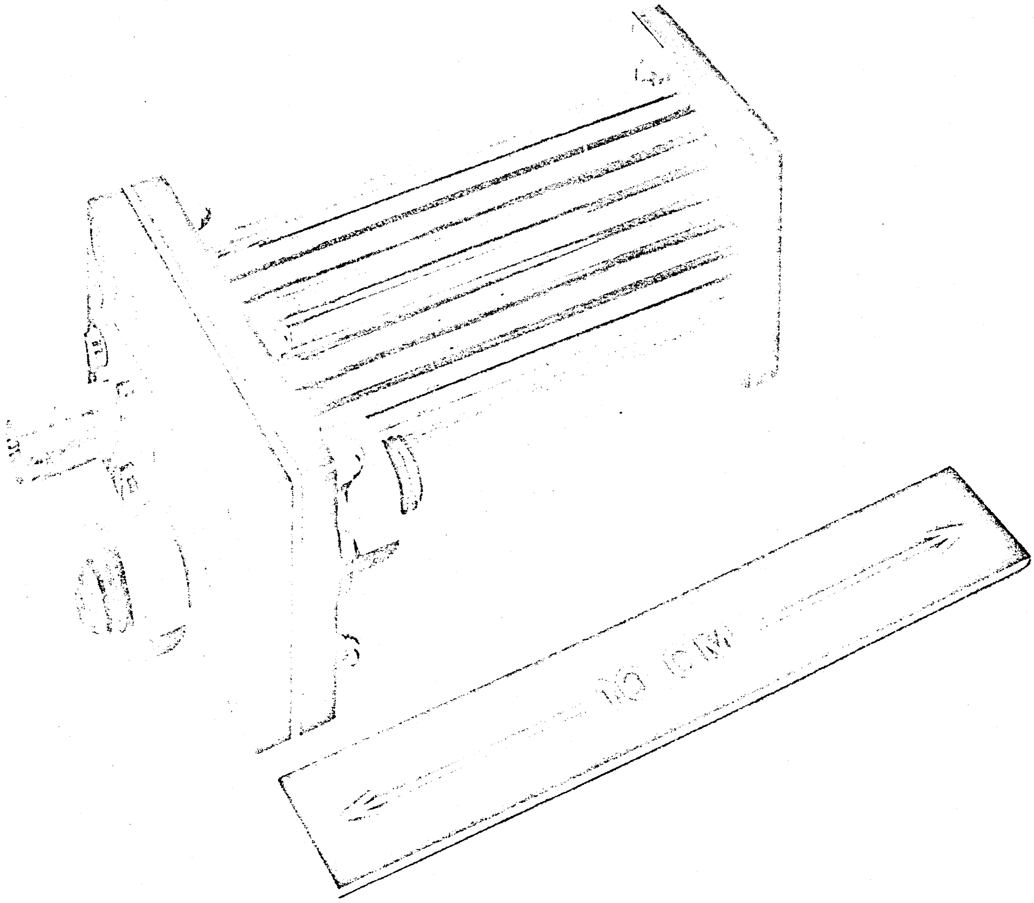


Fig. 15 Coaxial measuring shunt

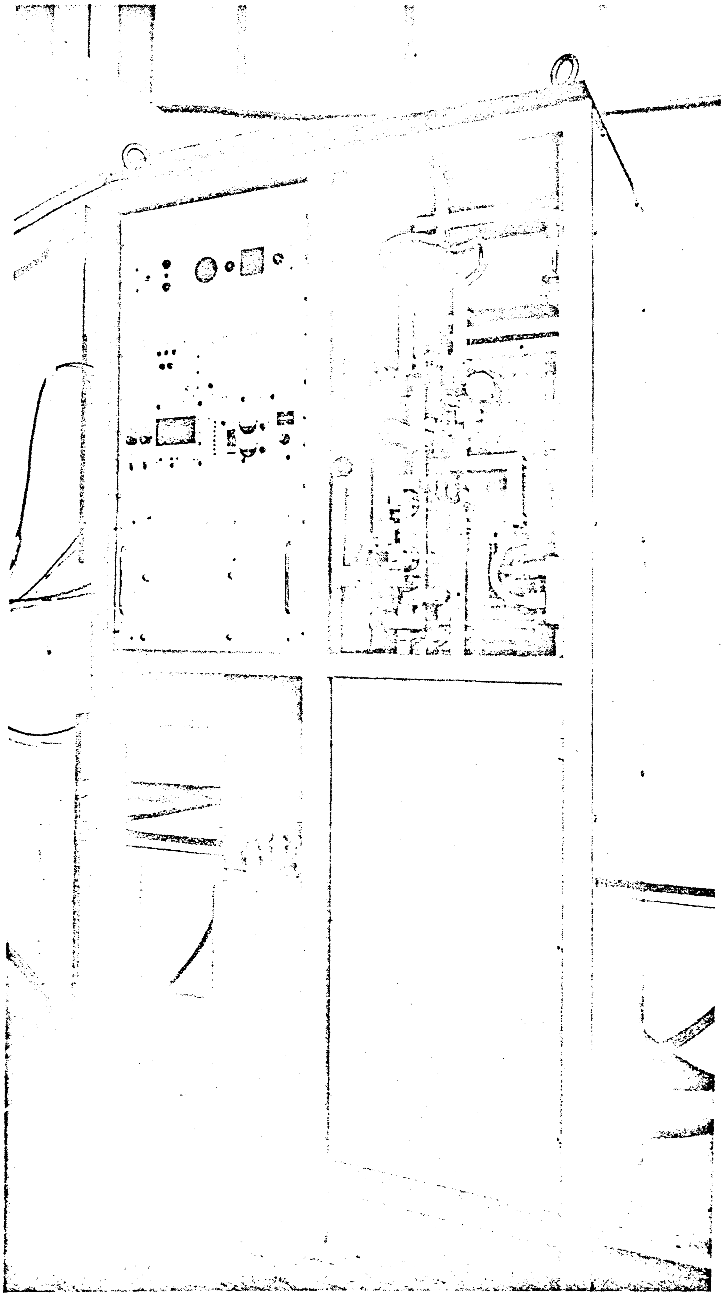


Fig. 16 Capacitor discharge assembly 2 kV, 6 kJ incorporating switching assembly, storage capacitors and d.c. charging supply in a single assembly cabinet

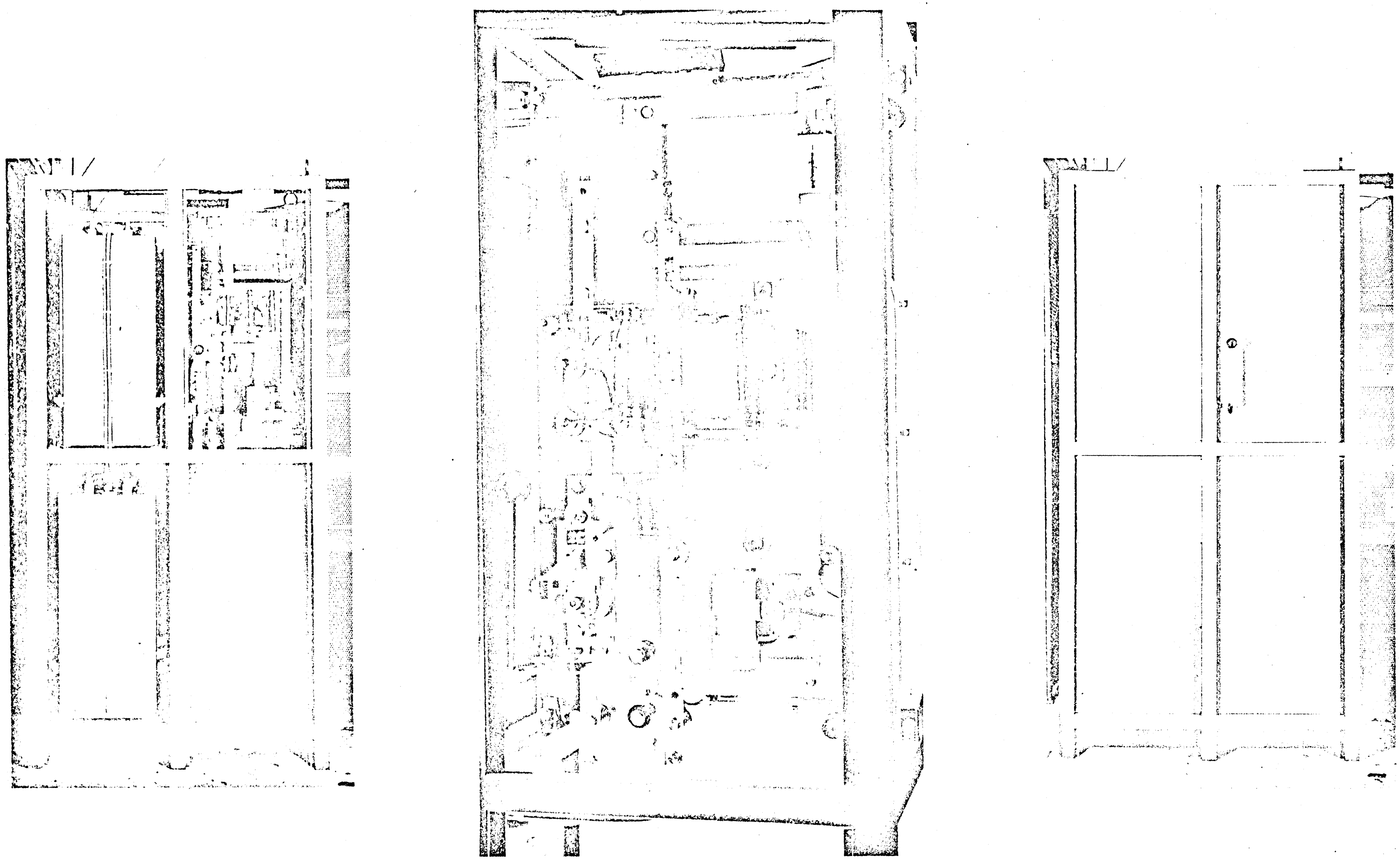


Fig. 17 Energy storage and discharge switching assembly 3 kV, 12 kJ
Shielded recuperation coil not yet mounted